TP 3682

FEASIBILITY STUDY FOR THE DEVELOPMENT OF AN EQUIPMENT HEALTH MONITORING & DIAGNOSTIC SYSTEM

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The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the "Transportation Development Centre", Transport Canada.

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17. Abstract

Instrumentation requirements for the diesel engine and related system are evaluated using risk analysis charts. The interrelationship of various parameters is stated and algorithms suggested. An investigation into the processing techniques revealed that it is essential to use probabilistic and statistical techniques to screen the data prior to analysis, otherwise diagnostic reliability is impaired.

The approach taken is believed to provide a useful compromise between minimizing engine and system disruption (for instrument installation and maintenance) and the provision of a sound diagnostic system.

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17. Resume

Ce rapport explique d'abord comment la détermination des paramètres de fonctionnement à surveiller a été fondée sur des statistiques montrant les probabilités de défaillances. Ensuite, il montre l'interrelation qui existe entre les divers paramètres retenus et suggère des algorithmes. Enfin, il établit, par une étude des techniques de traitement des données, qu'une approche probabiliste et statistique doit être adoptée, permettant de procéder à une sélection préliminaire des données de manière à assurer une bonne fiabilité du diagnostic.

On croit que l'approche préconisée est de nature à établir un bon compromis entre, d'une part, un temps d'immobilisation minimal (temps d'installation des appareils de mesure et temps d'entretien) et, d'autre part, l'obtention d'un diagnostic fiable.

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SUMMARY PAGE

This report studies the problem of deriving meaningful information and diognostics from a diesel engine using only externally applied sensors.

Current systems often use embedded sensors which can be a problem when repairing or retrofitting existing installations. Also, there are limitations because the diognostics are often unreliable as proper mathematical methods are not used.

In the proposed system a useful compromise has been made between disruption of the engine and system and the provision of a sound diognostic system. Instrument lists have been generated from risk charts. The interrelationship of parameter sets and algorithms for some thermodynamic relationships are stated.

Probalistic and statistical techniques were found to be essential for screening of the data prior to analysis. These techniques can impose considerable workload on the computer therefore they should be implemented in specially designed hardware.

Fault vector analysis, which results in a list of likely faults in their order of probability, is the best diagnostic method. It is a technique of least squares analysis where a measured vector is compared with predefined fault vectors.

The cost/benefit analysis indicates that it may only just be beneficial to install such a system based on fuel savings alone. However, if scheduled maintenance and manning levels can be reduced then significant savings are possible.

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1. INTRODUCTION

1.1 General

This is the final Phase I report by Eyretechnics Ltd. for "Transportation Development Centre", Transport Canada under contract 22ST.TB200-1-1528, Equipment Health Monitoring and Diagnostic System Development. It focuses on the requirements of a diesel engine diagnostic health monitoring system, and techniques are developed for improving diagnostic reliability.

1.2 Objectives

The objectives of this phase of the project are two-fold: first, to identify those measurable parameters of a diesel engine which would provide meaningful health diagnostic information and would not require significant disassembly or internal modification of the engine; and, second, to develop mathematical and statistical techniques for processing the collected data, thereby providing the most cost-effective solution by maximising the amount of information obtained from the minimum number of sensors.

1.3 Scope of Work

For the objectives cited, the study was restricted to the following tasks:

a. Perform computer-based literature search utilizing key-word logic to quantize applicable data.

b. Assess the literature obtained in the computer search to establish the state of the art.

c. Collate a system description applicable to the marine transportation environment.

d. Make visits, where required, to establish user requirements.

e. Evaluate the cost effectiveness of the system in the marine transportation environment.

1.4 Summary of the Task

Measurement Methods and Techniques, Part 3, considers the instrumentation requirements for the analysis of the health of each engine related system. Instrument lists are generated from risk charts with emphasis on the use of external sensing units. The interrelationship of various reading sets is stated and algorithms for some thermodynamic functions are suggested. Probabilistic methods are introduced for diagnosing engine and system faults.

The approach taken is believed to present a useful compromise between minimising engine and system disruption (for instrument installation and maintenance) and the provision of a sound diagnostic system.

An investigation into data processing techniques revealed that it is essential to use probabilistic and statistical techniques to screen the data prior to analysis. The investigation also revealed that one must be extremely careful when using a trend in a parameter, or set of parameters, to predict a future event; the confidence in which the prediction is made decreases as the length of the prediction increases.

Statistical calculations can be very tedious, imposing a considerable load on the computer system. Many small computers which are otherwise suitable for health monitoring application could not handle this extra load. For this reason, the statistical processing should be implemented in hardware rather than software, using hardware specially designed for the task. Two analog to digital convertor designs are discussed in Part 4 that inherently provide statistical processing or screening of the data.

Fault vector analysis, which results in a list of likely faults in their order of probability, is the best diagnostic method. It is a technique of least squares analysis where a measured vector is compared with predefined fault vectors.

The cost/benefit analysis indicates that it may only just be beneficial to install such a system based on fuel savings alone. However, if scheduled maintenance and manning levels can be reduced then significant savings are possible.

During the course of the task a visit was made to CN Marine in Halifax and user requirements were discussed with Mr. H. Coutts and staff. The PEI ferries MV Vacationland /MV Holiday Island were identified as possible test beds for the diagnostic system development.

2. THE REQUIREMENT

The marine diesel engine, like many machines of our daily acquaintance, has steadily increased in complexity and performance. Specific outputs once thought racey are now commonplace and current turbochargers would not look out of place on a jet plane.

Benefits have accrued in terms of efficiency and engine size, but the sophistication of design and materials has had to increase to cope with higher temperatures, speeds and loads. This in turn requires more precision in manufacture and tuning of the engine and tends to provide a greater capacity for self-destruction. Simply, there is less room for error.

Other recent events outside the realm of the diesel engine have resulted in massive increases in the cost of fuel, a trend unlikely to abate but one that redoubles the emphasis on the diesel engine's forte - thermal efficiency.

Collectively, these points demonstrate the need to assist the engine operator and maintainer by providing an accurate indication of the engine health by rapidly bringing to notice any malfunction or deterioration of performance.

The advent of the micro-computer has made possible a powerful new tool to provide this assistance. When combined with a set of measuring instruments on the engine, a special purpose micro-computer can become a monitor of engine health and a collector of engine information. In principle, a health monitor compares the actual values of engine parameters with those which ought to occur at the prevailing ambient conditions and levels of power and speed. If a difference is detected between the actual and the standard values, a warning is displayed and the data store is searched to provide diagnostic information to pinpoint the cause of the discrepancy. A single parameter fault may not contain conclusive evidence of a problem, but if two or three parameters show deviation the picture becomes much clearer and accurate diagnosis becomes feasible.

The ability of the micro-computer to record data can be useful in the event of an engine failure because a record of parameter values preceding the failure can provide a valuable aid to analysis. A suitable compromise is necessary here to ensure adequate records without incurring massive data storage.

Long-term storage, available through the micro-computer, can be employed to relieve the operator of some machinery logging functions. The total installed time of major components, hours of operation since last maintenance, and total energy produced are but a sample of the items which may usefully be logged to provide a measure of maintenance and configuration control.

Although it may appear that all of these functions fall into the 'nice to have' category rather than being essential, a number of factors concerning the modern working environment should be considered. First, the modern operator has often received a shorter training on more complex machinery than hitherto. Second, the machinery tends to be more reliable, thus reducing the operator's exposure to problems. And, third, operators have become familiar with computing devices in many aspects of life and expect to have them available as aids on the job.

The concept of the machinery health monitor is designed to satisfy these requirements and provide accurate information for tuning, rapid indication of malfunction, a logical approach to fault diagnostis, and accurate, reliable record keeping.

3. MEASUREMENT METHODS & TECHNIQUES

3.1 Parameter Selection

The measurement of engine related parameters, for the purpose of health monitoring, confers high demands on the instrumentation involved. It is vital that the measurement system exhibits greater longevity and reliability than the equipment being measured. This requirement is not lessened by the fact that problems often involve only small changes in parameters, necessitating high long-term stability of the instruments.

Considering these factors and the requirement to fit the instrumentation to existing equipment, some guidelines have been evolved:

a. High temperature or high stress pressure transducers are to be avoided because they do not possess either the required longevity or stability.

b. Pulse pick-up devices for speed and phase measurement of rotary parts are to be encouraged because they are rugged and do not lose accuracy. Total failure is easily detected.

c. Small signal output devices should be minimised. Specifically, low temperature thermocouples and piezo electric vibration pick ups should be avoided unless local amplification is used.

d. Greater use of computing power should be employed if instrumentation can be simplified or reduced as a consequence. Probablistic techniques may certainly be used to improve the accuracy of parameter value establishment.

e. Where compatible with accuracy requirements, the 'commercial' type of instrument sensing heads should be used to provide ruggedness and reliability.

The use of a health monitor is based on the assumptions that malfunctions will occur, that these malfunctions can be detected, and that corrections may be applied before extra costs are involved. Such costs may arise due to additional fuel consumption, secondary damage or unscheduled shut down of the plant.

Ideally, the structure of the health monitor should include the definition of all malfunctions which may occur. In equipment as complex as a modern diesel engine, this is an impossible task, but with knowledge of the history of a particular installation, a reasonably sized set of potential malfunctions may be generated.

It is necessary to specify instrumentation and monitoring methods to detect the presence, or absence, of each member of the malfunction set.

Each engine installation comprises several systems, all of which contain risk of malfunction to the installation. These systems are defined here as the fluid flow paths and rotating element assemblies. Thus, the set of malfunction risks is contained within the following subsets:

a. Combustion air path.

b. Fuel oil path.

c. Lub oil path.

d. FW coolant path.

e. SW coolant path.

f. Main engine mechanical.

g. Turbocharger mechanical.

h. Starting system.

j. Vapour and fire detection.

Although these systems are not independent they do provide a useful structure for organization of the monitor.

Each system contains components which are considered to be at risk of failure due to some indeterminate aspect of its operation. For instance, the SW heat exchanger may become clogged with seaweed, the starting air valve may corrode or fuel injectors may burn or clog with coke.

A typical set of risks is listed in subsection 3.2 and parameters are selected which will permit detection should a failure from the risk set occur.

The listing of the computation required to identify the failure serves as the basis for the computing algorithm.

3.2 Risk Analysis Charts

The risk analysis charts have been drawn up for a general diesel engine installation and represent typical hazards which may be encountered. A particular diagnostic system design would incorporate the actual installation details together with any known risks learned from experience with the machinery or similar installation. It is emphasized that the application of the engine has a strong bearing on the true risks with such factors as unmanned operation versus highly skilled operators, continuous operation versus occasional duty, and constant high power versus widely varying load being but a small sample of the frequently encountered variations.

An attempt has been made to demonstrate the interactions desirable within the computing algorithms of the system. It is by this linking of observed relationships that the diagnostic computation process can improve its probability of accuracy. For example if the lub oil temperature is seen to be high and the fresh water circulating pump output pressure is low, the problem is probably in the fresh water system rather than the lub oil.

It may also be noted that even when no instrument is installed to measure a particular parameter an automated prompt can be used to request that a manual reading be taken and entered into the computer.

COMPONENT	TASK	RISK	REASON	DETECTION	COMPUTE	INTERACTION	DIAGNOSTIC
BOOST PUMP	DELIVER F.O. TO ENGINE	PUMP FAILURE	MECHANICAL	P (BOOST SUCTION) P (BOOST)	-	CHARGE PUMP	BOOST PUMP SUCTION LOW BOOST PRESSURE LOW
FILTER/COALESCER	REMOVE DIRT & WATER FROM F.O.	BLOCKAGE	F.O. CONTAMINATION OVERDUE ELEMENT CHANGE	DELTA P (F.O. FILTER)	-	-	F.O. FILTER BLOCKED
CHARGE PUMP	PRESSURE F.O.	PUMP FAILURE	MECHANICAL	P (F.O. CHARGE)	-	-	F.O. CHARGE PRESSURE
INJECTION PUMP	METER F.O. TO ENGINE	TIMING FLOW CALIBRATION MECHANICAL TAPPETS	SETTING ERRORS DETERIORATION	CYL. VIBRATION TURNING MOMENT T (EXHAUST GAS) TIMING RACK POSITION	TIMING INJECTION PERIODS RACK POSITION	ENGINE ROTATIONAL SYSTEM COMBUSTION AIR SYSTEM	TIMING ERROR FUEL FLOW HIGH/LOW

Table 1 System - Fuel Oil

COMPONENT	TASK	RISK	REASON	DETECTION	COMPUTE	INTERACTION	DIAGNOSTIC
STORAGE TANK	RESERVOIR	LOW CONTENTS	NEEDS FILLING	LEVEL	-	-	LO STORAGE TANK LOW
TOP UP PUMP	TRANSFER TO DAY TANK MEASURE ENGINE CONSUMPTION	PUMP FAILURE HIGH CONSUMPTION	ELECTRO MECHANICAL ENGINE PROBLEMS	FLOW TOTALISER DAY TANK LEVEL FLOW TOTALISER	FLOW WHEN PUMP ON - MEDIUM TERM FLOW vs ENGINE POWER	- - ENGINE MECHANICAL	LO TOP UP PUMP FAILED LO DAY TANK LOW ENGINE LO CONSUMPTION HIGH
DAY TANK	SERVICE RESERVOIR	TIME EXPIRED L.O. CONTAMINATED L.O.	AGE FUEL DILUTION ACID BUILD UP	L.O. CHANGE LOG VISCOMETER Ph MEASUREMENT	AUTO REQUEST FOR MANUAL MEASUREMENT	- - -	CHANGE L.O. L.O. VISCOSITY LOW L.O. Ph LOW
MAIN PUMP	SUPPLY GALLERIES	NO SUPPLY PUMP FAILURE	VALVE SHUT MECHANICAL WEAR	P(LO PUMP IN) P(LO PUMP OUT)	P(LO PUMP IN) LOW P(LO PUMP OUT) ZERO P(LO PUMP OUT) vs ENGINE SPEED & T(LO DAY TANK)	ENGINE SHUT DOWN ENGINE SHUT DOWN ENGINE MECHANICAL	L.O. PUMP STARVATION L.O. PRESSURE FAILURE L.O. PRESSURE LOW
FILTER	REMOVE PARTICULATES	BLOCKAGE	AGE PISTON BLOW BY	DELTA P(LO FILTER)	TIME FITTED		LO FILTER HIGH DELTA P RAPID BLOCKAGE OF LO SUPPLY FILTER
COOLER	COOL L.O.	FOULING LEAKAGE	VARNISH SLUDGE CORROSION	T(LO IN) T(LO OUT) T(FW IN) T(FW OUT) OIL IN WATER	LMTD EFFECTIVENESS	FW SYSTEM	L.O. COOLER TROUBLE L.O. COOLER LEAKAGE
COOLER CONTROL	MAINTAIN L.O. TEMP	CALIBRATION DRIFT HYSTERESIS FAILED OPEN FAILED CLOSED	AGE STICKING MECHANICAL	T(LO OUT)	T(LO OUT) TREND RATE OF CHANGE LOW HIGH	-	L.O. TEMP CONTROL TROUBLE
PRV	MAINTAIN L.O. PRES	SYSTEM P HIGH LOW ERRATIC	MECHANICAL	P(LO ENGINE)	P(LO ENGINE) vs T(LO DAY TANK)	P(LO PUMP OUT) ENGINE MECHANICAL	LO PRV TROUBLE
PRE-LUB PUMP	PRE-START PRESSURIZE	PUMP FAILURE	ELECTRO-MECHANICAL	P(LO ENGINE)	P(LO ENGINE) LOW AT START COMMENCE	START SEQUENCE	LO NO PRE LUB
SCAVENGE PUMP	SCAVENGE SUMP TO DAY TANK	PUMP FAILURE	MECHANICAL	P(LO SCAV OUT) (SMOOTHED) SUMP LEVEL	- -	- -	LOW SCAV PRESSURE LOW LO SUMP LEVEL HIGH
SCAVENGE FILTER	PARTICULATE FILTER	FOULING	SLUDGE/CARBON BUILD UP	DELTA P(LO SCAV FILT)	TIME TO FOUL	ENGINE MECHANICAL	LO SCAV FILT HIGH DELTA P RAPID BLOCKAGE OF LO SCAV FILTER
MAGNETIC CHIP DETECTOR	DETECTION OF WEAR PARTICLES	MAGNETIC PARTICLES COLLECTED	ENGINE DETERIORATION	MANUAL OR ELECTRICAL	-	ENGINE MECHANICAL	MAGNETIC CHIPS IN LO

Table 2 System - Lub Oil

COMPONENT	TASK	RISK	REASON	DETECTION	COMPUTE	INTERACTION	DIAGNOSTIC
HEADER	WATER RESERVOIR	CONTENTS LOW Ph LOW OIL CONTAMINATION	LEAKAGE/EVAPORATION INADEQUATE TREATMENT SEAL OR COOLER	LEVEL MANUAL-AUTO PROMPT MANUAL-AUTO PROMPT	TREND	 L.O. SYSTEM	FW HEADER LEVEL LOW FW PH LOW OIL CONTAMINATION IN FW
CIRCULATING PUMP	SUPPLY ALL FW SYSTEMS	PUMP FAILURE	ELECTRO-MECHANICAL	P(FW PP OUT)	-	ENGINE MECHANICAL	FW CIRC PUMP TROUBLE
AFTER COOLER	COOL T/C DISCHARGE	AIR LEAKAGE LOW HEAT EXCHANGE	TUBE NEST LEAKS AIR IN FW	AIR TRAP T(A/C AIR IN) T(A/C AIR OUT) T(A/C FW IN) T(A/C FW OUT)	LMTD EFFECTIVENESS	COMBUSTION AIR SYSTEM	AFTER COOLER TROUBLE
L.O. COOLER	COOL L.O.	LOW EFFECTIVENESS LEAKAGE	TRAPPED AIR CORROSION	AIR TRAP T(L/C LO IN) T(L/C LO OUT) T(L/C FW IN) T(L/C FW OUT)	LMTD EFFECTIVENESS	L.O. SYSTEM	AIR IN L.O. COOLER L.O. COOLER TROUBLE
CYLINDER BLOCK WATER JACKET	COOL BLOCK	BLOCKAGE HIGH HEAT RELEASE	CORROSION/FURRING ENGINE FAULT	P(JACK IN) P(JACK OUT) T(JACK IN) T(JACK OUT)	DELTA P (JACK) HIGH DELTA T (JACK) vs POWER	ENGINE MECHANICAL	WATER JACKET BLOCKAGE ENGINE HEAT RELEASE HIGH
FW COOLER	REJECT FW HEAT TO SW	BLOCKAGE LOW EFFECTIVENESS	CORROSION/FURRING	T(F/W CLR IN) T(F/W CLR OUT) T(CLR SW IN) T(CLR SW OUT) AIR TRAP	LMTD EFFECTIVENESS	-	FW COOLER TROUBLE AIR IN FW COOLER
FW COOLER CONTROLS	DIVERT FW FLOW TO MAINTAIN HEADER TEMPERATURE	SET POINT DRIFT ERRATIC CONTROL CONTROL LOSS	WEAR HYSTERESIS CONTROL FAILURE		TREND ALLOW FOR WARM UP	-	FW COOLER CONTROL TROUBLE
BLOCK HEATER	MAINTAIN FW TEMP WHEN SHUT DOWN	HEATER FAILURE	ELECTRICAL	T(JACK OUT)	T(JACK OUT) BELOW SET MINIMUM	-	BLOCK HEATER TROUBLE

Table 3 System - Fresh Water Coolant

COMPONENT	TASK	RISK	REASON	DETECTION	COMPUTE	INTERACTION	DIAGNOSTIC
SEA CHEST	COLLECT/SCREEN SW	BLOCKAGE	WEED MOLUSKS	P(SW PUMP IN)	P(SW PUMP IN) BELOW NORMAL	-	SEA CHEST FOULING
SW PUMP	DELIVER SW TO COOLER	PUMP FAILURE	ELECTRO MECHANICAL	P(SW PUMP OUT)	DELTA P(SW PUMP)	-	SW PUMP TROUBLE
FW COOLER	COOL FW	BLOCKAGE	WEED MOLUSK CORROSION	P(FW COOLER SW IN) P(FW COOLER SW OUT)	DELTA P(FW COOLER SW)	FW SYSTEM	FW COOLER SW BLOCKAGE
SEA WATER RECIRCULATION CONTROL	PREVENT SEA CHEST ICING	CONTROL FAILURE	MECHANICAL	T(SW PUMP IN)	T(SW PUMP IN) BELOW SET MINIMUM	-	SEA WATER RECIRCULATION TROUBLE

Table 4 System - Sea Water Coolant

COMPONENT	FUNCTION	RISK	REASON	DETECTION	COMPUTE	INTERACTION	DIAGNOSTIC
CRANK ASSEMBLY	-	SLACK BEARINGS	WEAR EROSION	VIB (BLOCK) P(LO ENGINE) T(LO DAY TANK)	VIB PATTERN RECOG. P(LO ENGINE) CORRECTED FOR T(LO DAY TANK) vs N		CRANK BEARINGS SLACK LO PRV
		TORSIONAL BENDING	OVER TORQUE VIBRATION	N(FLYWHEEL) N(DAMPER)	PHASE DIFFERENCE ALONG CRANK (CONSTANT) (VIBRATIONAL)		CRANK TORSION BEND CRANK TORSIONAL VIB.
PISTON	-	RING LEAKAGE	WEAR	CRANKCASE BREATHER FLOW	BREATHER FLOW vs TORQUE & T(INLET)		HIGH BREATHER FLOW
		PISTON SLAP	WEAR	VIB (BLOCK)	VIB PATTERN RECOG. TREND DETECTION		PISTON SLAP INCREASING
CYLINDER HEAD	-	GAS/WATER LEAKS HEAD WARPAGE	GASKET BLOWN	P(JACK OUT)	P(JACK OUT) HIGH	FW SYSTEM	FW CONTAMINATED- CYLINDER LEAK
EXHAUST VALVE	-	LEAKAGE	BURNT/WARPED SEAT	T(EXHAUST) TORQUE	DELTA T(EXHAUST) DELTA TORQUE PATTERN RECOG.	INJECTION QUANTITY	HIGH TEMP. EXHAUST CYL. EXHAUST VALE LEAKAGE
	TORQUE (TURNING MOMENT)	NON-UNIFORM	UNEQUAL CYLINDER OUTPUT UNEQUAL FUEL INJECTION	ACCELERATION AT OUTPUT SHAFT (SMALL INTERVAL)	N AT PEAK TORQUE PHASE FOR EACH CYLINDER	TORSIONAL VIB.	UNEQUAL CYLINDER EFFORT CYL. NO. ____ HIGH/LOW
	INJECTION TIMING	MIS-TIMED	ORIGINAL SETTING DRIFT WEAR	CRANK PHASE VIB (CYLINDER)	PHASE OF IGNITION POINT	QUALITY OF IGNITION	INJECTION TIMING ERROR CYL. NO. $\pm$ ... DEGREE
	IGNITION QUALITY	DETONATION	POOR ATOMISATION LOW CETANE TIMING ERROR LOW COMPRESSION	VIB(CYLINDER) P(T/C OUTPUT)	VIB ANALYSIS PATTERN RECOG. P(T/C OUTPUT) vs POWER	INJECTION TIMING COMBUSTION AIR SYS	DETONATION CY. NO. ____ CYLINDER INPUT PRESSURE LOW
	POWER	-	-	ENGINE SPEED (SHORT INTERVAL)	FREE ACCELERATION RATE		(POWERSPEED CURVE)
	FRICTION	INTERNAL FRICTION INCREASED	MECHANICAL DETERIORATION	ENGINE SPEED (SHORT INTERVAL)	FREE DECELERATION RATE		(FRICTION POWER vs SPEED)

Table 5 System - Engine Mechanical

COMPONENT	TASK	RISK	REASON	DETECTION	COMPUTE	INTERACTION	DIAGNOSTIC
COMPRESSOR	CENTRIFUGALLY PRESSURISE INTAKE AIR	FOULING	OIL, DIRT, SALT, ICE INGESTION	T(T/C AIR IN) P(T/C AIR IN) T(T/C AIR OUT) P(T/C AIR OUT) N(T/C)	MACH NO. (N/ T) EFFICIENCY vs MACH NO. FREEZING RANGE	COMBUSTION AIR	T/C COMP. FOULED-CALL WASH T/C COMP. ICING WARNING
ROTOR	-	UNBALANCE	FOD EROSION	VIB(T/C)	MEAN VIB LEVEL	-	T/C VIBRATION HIGH
		FRICTION INCREASE	RUB BEARING, SEAL FAILURE	RUN DOWN TIMER	TIME BETWEEN SPEED SET POINTS ON RUN DOWN	-	T/C RUNDOWN TIME LOW
TURBINE	RECOVER GAS EXPANSION ENERGY	BLADE DETERIORATION	HOT CORROSION FOULING (SOOT)	T(TURB IN) P(TURB IN) T(TURB OUT) P(TURB OUT) N(T/C)	MACH NO. (N/√T) EFFICIENCY vs MACH NO.	COMBUSTION AIR	T/C TURBINE FOULING-CALL WASH

Table 6 System - Turbo Charger

COMPONENT	TASK	RISK	REASON	DETECTION	COMPUTE	INTERACTION	DIAGNOSTIC
RESERVOIR	HOLD HP AIR	LOW PRESSURE	HP AIR SYSTEM	P(HP RES)	P(HP RES) BELOW NORM	-	HP AIR PRESSURE LOW
START VALVE	ADMIT START AIR	NON OPENING NO SHUT OFF	MECHANICAL	P(START HP AIR)	RISE & FALL IN P(START HP AIR) DURING START SEQUENCE	START SEQUENCE	START VALVE TROUBLE
REGULATOR	REDUCE HP AIR TO START PRESSURE	OUTPUT PRESSURE HIGH/LOW	MECHANICAL WATER ICE	P(START AIR)	P(START AIR) WITHIN TOLERANCE	START SEQUENCE	START HP REGULATOR TROUBLE
FILTER	REMOVE DIRT	BLOCKAGE	DIRT OR WATER	N(CRANK)	N(CRANK) BELOW START SPEED	ENGINE MECHANICAL	ENGINE START SPPED LOW

Table 7 System - Starting Air

3.3 Transducer Requirements

The following lists of transducers and diagrams of typical fluid circuits indicate the instrumentation required for the computerized system.

Manual instruments for the more important functions would still be required, as is normal practice.

3.3.1 Pressure

INLET AIR ABSOLUTE
AIR FILTER DIFFERENTIAL
BELLIMOUTH DIFFERENTIAL
TURBO CHARGER AIR OUTLET
AFTER COOLER AIR DIFFERENTIAL
TURBO CHARGER TURBINE INLET
TURBO CHARGER TURBINE OUTLET
FUEL BOOST PUMP SUCTION
FUEL BOOST PUMP DISCHARGE
FUEL FILTER DIFFERENTIAL
FUEL CHARGE PUMP DISCHARGE
LUB PRESSURE PUMP SUCTION
LUB PRESSURE PUMP DISCHARGE
LUB FILTER DIFFERENTIAL
LUB GALLEY
LUB TURBO CHARGER
LUB SCAVENGE PUMP DISCHARGE
LUB SCAVENGE FILTER DIFFERENTIAL
FW PUMP DISCHARGE
GW ENGINE JACKET DIFFERENTIAL
FW COOLER DIFFERENTIAL
SW PUMP SUCTION
SW PUMP DISCHARGE
SW COOLER DIFFERENTIAL
HP AIR RESERVOIR
HP AIR REGULATOR DISCHARGE
STARTING AIR

3.3.2 Temperature

INLET AIR
TURBO CHARGER AIR OUTLET
AFTER COOLER OUTLET
EXHAUST - EACH CYLINDER
TURBO CHARGER TURBINE INLET
TURBO CHARGER TURBINE OUTLET
FUEL BOOST PUMP INLET
LUB TANK
LUB ENGINE INLET
LUB ENGINE OUTLET
FW LUB COOLER INLET
FW LUB COOLER OUTLET
FW AFTER COOLER INLET
FW AFTER COOLER OUTLET
FW ENGINE JACKET INLET
FW ENGINE JACKET OUTLET
FW COOLER INLET
FW COOLER OUTLET
FW HEADER
SW PUMP INLET
SW COOLER OUTLET

3.3.3 Miscellaneous

CRANKSHAFT TACHOMETER - DRIVE END PHASE
CRANKSHAFT TACHOMETER - DAMPER END PHASE
TURBO CHARGER TACHOMETER
VIBRATION - EACH CYLINDER HEAD
VIBRATION - CRANKCASE
VIBRATION - TURBO CHARGER
NOISE - EXHAUST STACK
LEVEL - LUB TANK
LEVEL - LUB STORAGE TANK
LEVEL - FW HEADER
AIR TRAP LEVEL - LUB COOLER
AIR TRAP LEVEL - AFTER COOLER
AIR TRAP LEVEL - FW COOLER
LUB CHIP DETECTOR
RACK POSITION

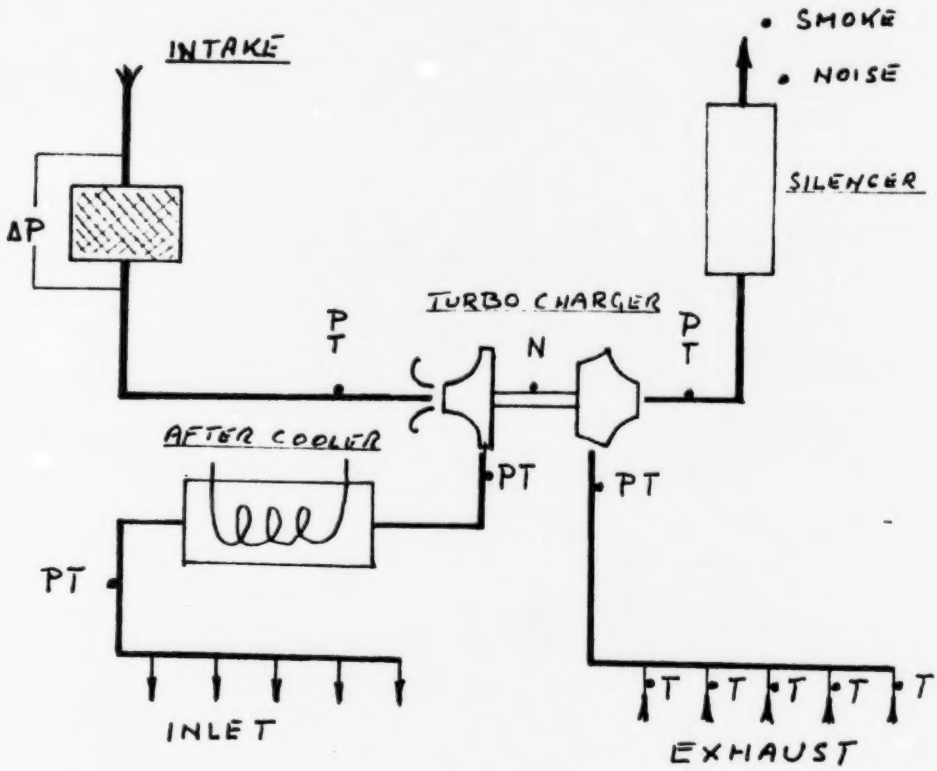

Figure 1 Combustion Air System Instrumentation

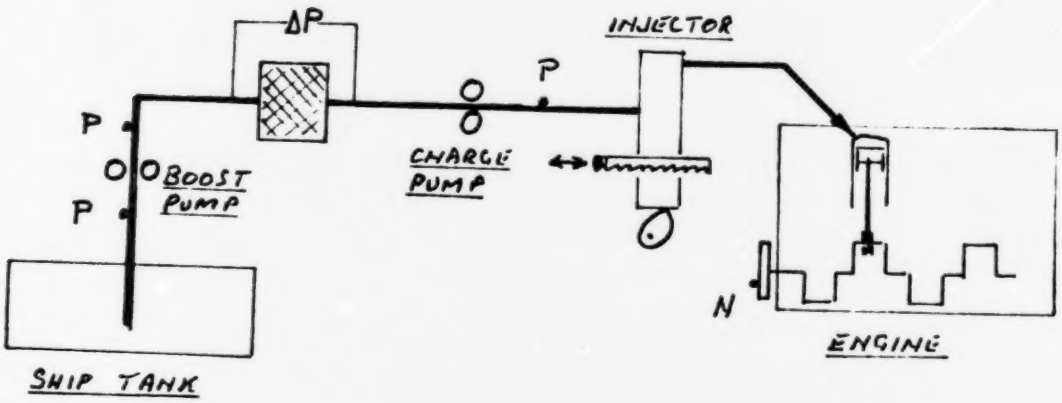

Figure 2 Fuel Oil System Instrumentation

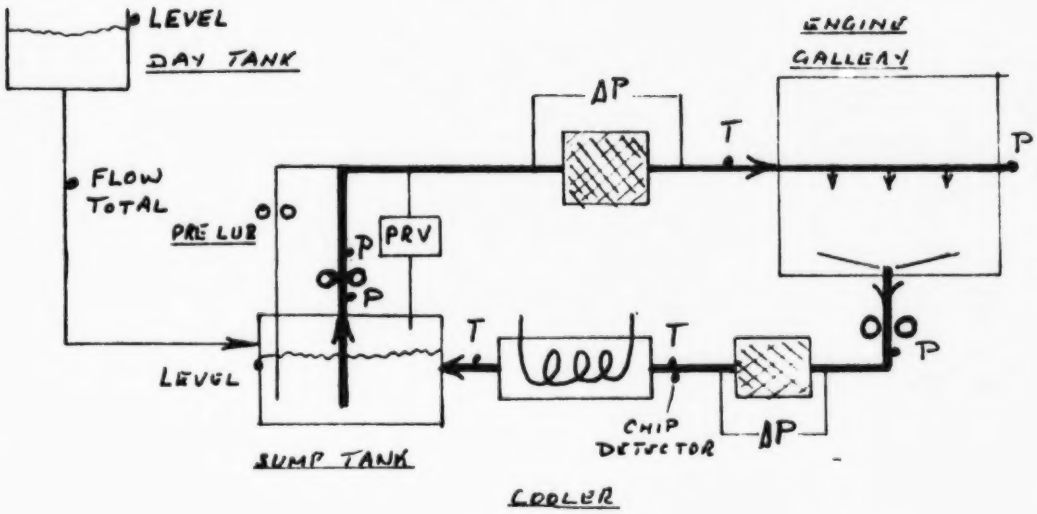

Figure 3 Lub Oil System Instrumentation

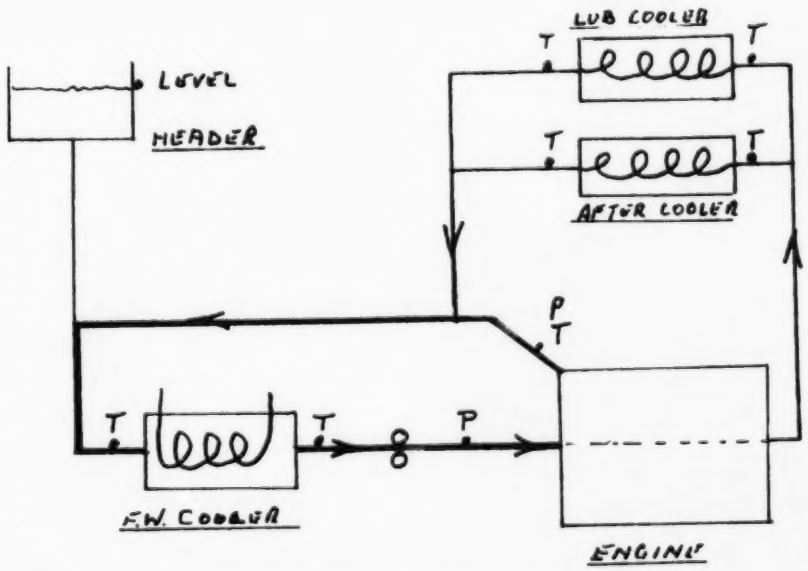

Figure 4 Fresh Water System Instrumentation

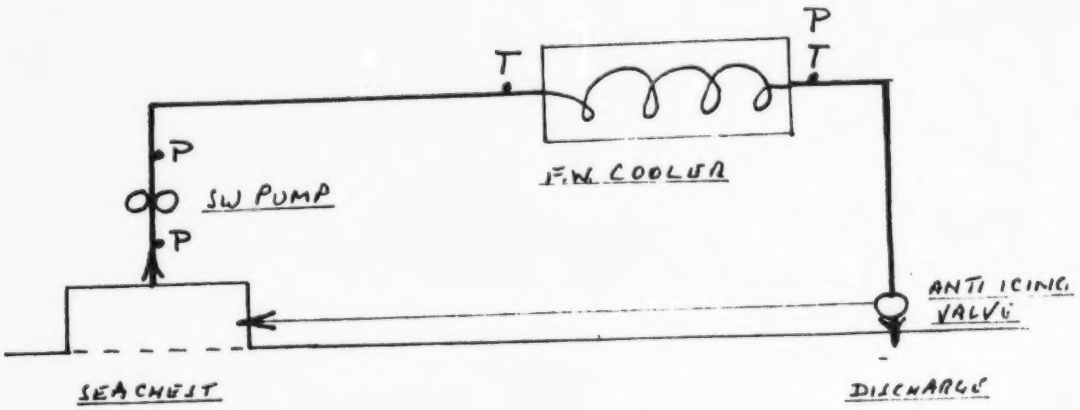

Figure 5 Sea Water System Instrumentation

3.4 Computation Requirements

It is fundamental to the health monitoring system proposed that the instrumentation employed is external to the engine and is applied simply. The detection of engine health is by computed deduction from several external sensor signals, the most important being vibration pickups. Research by Priede et al. has shown that the vibration exhibited by the cylinder head zone has a clear signature for the point of ignition for the subsequent quality of burning(1). The recognition of this signature and its computed combination with crankshaft rotation data provides a reading of the actual ignition timing; further analysis of the vibration wave form provides an ignition quality indication complete with the existence and degree of detonation. By this means, late injection may be separated from late ignition caused by poor quality injection.

Another powerful tool is the detailed incremental analysis of engine flywheel speed. From this input the contribution of each expansion stroke to the engine power may be computed, and the similarity of the power output of each cylinder by be gauged. Strong or weak cylinder readings may be used for diagnostic deduction of injection quantity errors and valve problems.

By placing a second crankshaft speed pickup at the opposite end of the shaft it is possible to gauge torsional vibration of the shaft and to detect long-term torsional bending.

Although the foregoing provides very valuable pointers to engine health and aids to tuning, prevention of problems is of the utmost importance. It is general experience that many engine problems result from deficiencies of supporting systems; it is therefore a major feature of the proposed monitor that each support system be closely monitored and diagnosed for correct operation.

The simplest monitoring occurs where the health of a component is represented by a single parameter. Such a component is an oil pressure relief valve which has a very narrow range of correct relief pressure so that any excursion outside this range is indicative of a problem. However, many engine or system components are more complex than an oil pressure relief valve and the health related parameter is related to at least one other variable. For instance, the efficiency of the turbocharger compressor can be expected to vary with inlet Mach numbers (N/T), perhaps in a non-linear manner. Here the computer must calculate the efficiency from four input signals and compare, probably via a "look up" table, the actual efficiency with the normal at the prevailing Mach number. The extent of any deviation must be compared with allowable limits to determine the component health or extent of deterioration.

This dynamic monitoring is of particular value in the hot section of the engine. It becomes quite feasible to diagnose leaking exhaust valves or excessive fuel injection at intermediate power levels when overtemperature conditions have not occurred thus preventing secondary damage which may occur if high power is delivered and limits are exceeded.

Another feature of the proposed health monitor is the ability to recall the values of all measured parameters over the previous one-hour operating period. This is particularly valuable in the event of a real or suspected equipment malfunction. By this means a replay of the appropriate parameters preceding an event are available for inspection, plotting or other analysis to help determine the cause of a failure, the consumption of a fluid or to track down an illusive intermittent problem.

To avoid excessive storage of redundant data, the detailed records would be erased after the one hour of storage, leaving a permanent record of perhaps one reading set per hour.

Finally, the computing function would maintain a permanent record of maintenance activities carried out on the machinery. Such functions as running hours, time since installation, total energy produced, maximum power developed and many other functions of interest to specific operators would be logged in computer accessible form for many components of the installation.

This information provides a level of configuration control when modifications are being introduced and is a reliable base for machinery cost control.

3.5 Component Algorithms

3.5.1 Turbo Charger Compressor Efficiency

LET P_1 = PRESSURE AT ENTRY

T_1 = TEMPERATURE AT ENTRY

P_2 = PRESSURE AT EXIT

T_2 = TEMPERATURE AT EXIT

γ = 1.4 (AIR)

$$\text{ADIABATIC EFFICIENCY} = \frac{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}} - 1}{\frac{T_2}{T_1} - 1}$$

3.5.2 Turbo Charger Turbine Efficiency

γ = 1.33 (EXHAUST GASES)

$$\text{ADIABATIC EFFICIENCY} = \frac{1 - \frac{T_2}{T_1}}{1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}}$$

3.5.3 Heat Exchanger Performance

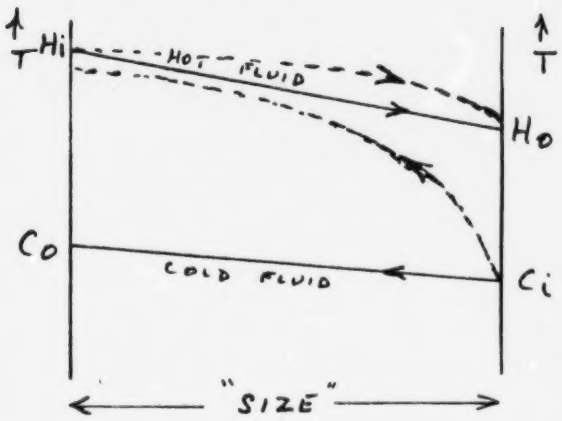

Figure 6 Heat Exchanger Temperature Distribution

The full lines indicate the temperature changes across a cooler when at ideal or design conditions. When operating at off design conditions, as when one fluid flow has been reduced by throttling or blockage, the temperature distribution approaches that shown by the broken lines.

An indication of the actual performance relative to the ideal may be obtained from the following equation:

$$\text{Figure of merit} = \frac{1/2\left[(Hi + Ho) - (Ci + Co)\right]}{\dfrac{(Hi - Co) - (Ho - Ci)}{\log_e\left(\dfrac{Hi - Co}{Ho - Ci}\right)}}$$

3.6 DIAGNOSTIC CONCEPTS

As mentioned earlier, the presence of a particular fault in the engine system will probably cause several parameters to deviate from their normal values. If enough parameters were measured the diagnosis of any particular fault could be complete and sure, but this would require a quantity of instrumentation that is neither desirable nor practical. Instead, the use of probability is introduced and the concept established that the diagnostic readout is not absolute but rather a tool to assist the machinery operator's surveillance function with probable diagnosis.

The diagnostic process commences by periodically collecting all the steady state errors from the dynamic condition monitor. Any such error which is outside its tolerance range is the first clue that a machinery or an instrument fault exists.

In the simplest form of diagnosis, only the direction of this fault is observed and is compared with a truth table of all listed faults. This will narrow down the diagnosis to a minority of the listed fault possibilities. A further error will give a finer diagnosis, and if four or five errors are present the confidence level of the diagnosis can be very high.

A refinement of the diagnostic process is offered by a mathematical technique known as the fault vector method. This is best considered as a means of summing all error magnitudes which exist at one time and comparing the resultant of these with the errors which would be produced by each of a list of anticipated faults. An in-depth description of this technique is provided in Section 4.4.

The advantages offered by fault vector analysis are that a fault condition is recongized earlier than with other methods and the chances of detecting instrumentation faults are higher. Indeed, the list of faults would include those of the instrument system thus reducing the chance of false alarms.

4. DATA PROCESSING TECHNIQUES

4.1 Analog to Digital Conversion

The majority of monitoring and data logging systems in use today sequencially scan the analog inputs in a fixed order at a constant rate. This technique is adequate if it can be assumed that there is no noise or unwanted periodic signals present at the input. In a properly installed and maintained system noise levels should be low enough as to not be significant, but there are two sources of noise that, properly dealt with, can greatly improve system reliability and user acceptability, namely:

a. Spurious noise signals from switching of large loads, solenoids etc, and transducer or connecting cable failure.

b. Cyclic variations - These are always present in a dynamic system such as an engine and will cause errors in reading, due to the sampling techniques usually employed and varying response times between transducers.

The noise could be eliminated at the input by heavy filtering but this method would slow response times and leads to further inaccuracies.

An alternative approach to the noise problem is to analyse the data statistically. Noise can be identified by its statistical structure and rejected, and the cyclic variations can be eliminated by randomized sampling and averaging.

The statistical structure of a noise voltage can be assumed to be random and with a constant probability density function. The input data would normally be expected to be constant except for the cyclic variations. The changes in operating conditions should not affect this assumption because they are relatively slow. By monitoring the variance of the incoming data it should be possible to easily identify which data contains excessive noise. The difficulty arises in separating the noise from the data; however, this should not be necessary. If the noise is sporadic then the data containing noise can be rejected with no consequence. If the noise is more continuous then the operator can be alerted and the problem investigated.

An essential condition for any statistical analysis is that the data be sampled at random. Standard analog to digital convertor (ADC) systems do not meet this requirement. Two proposed methods of meeting the requirement are presented in Figures 7 and 8.

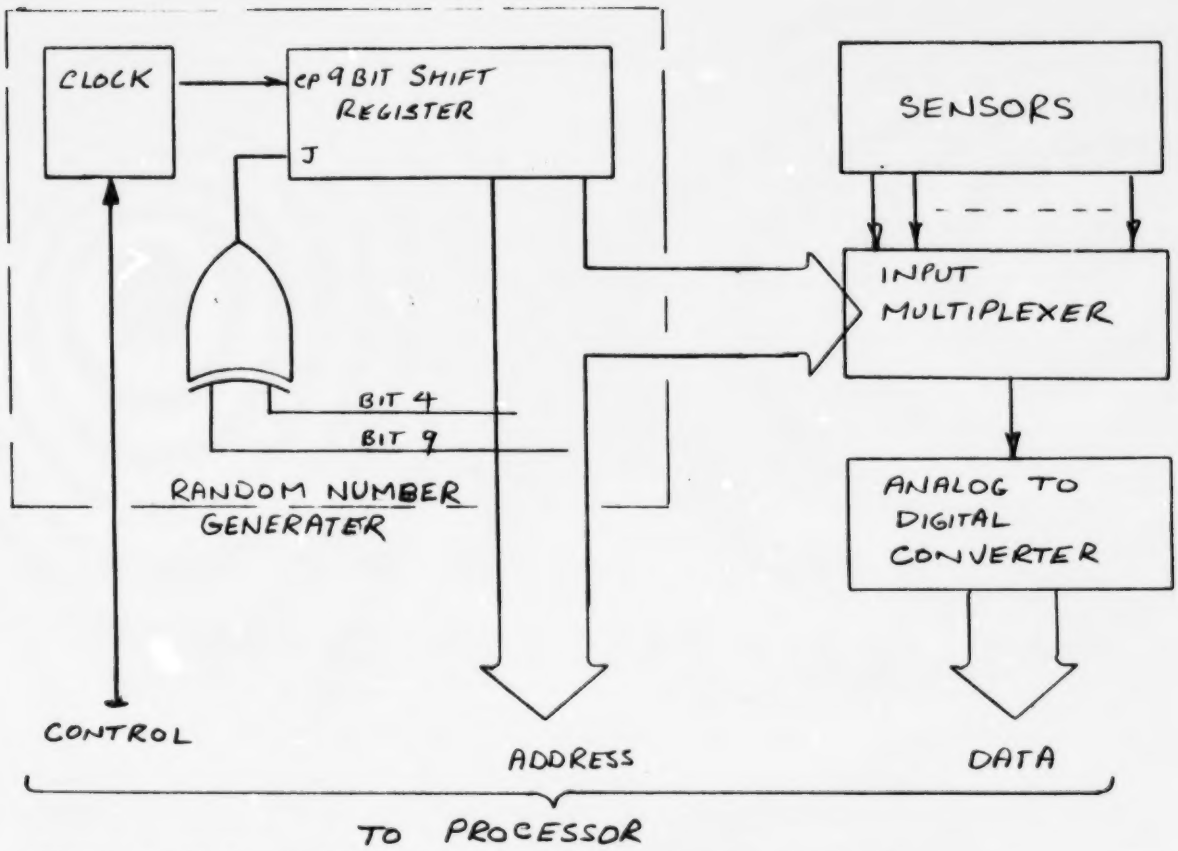

Figure 7 Analog to Digital Convertor - Randomized Input Selection

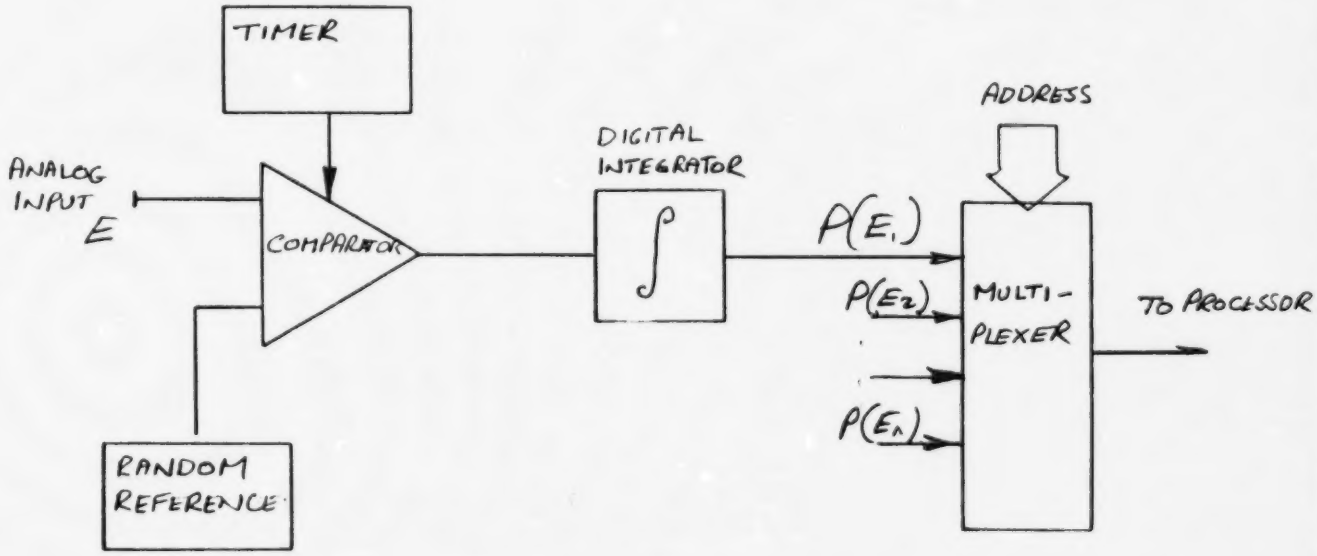

Figure 8 Analog to Digital Convertor - SEM Method

In Figure 7 a pseudo-random number generator is used to control address selection of the ADC input multiplexer. If a sufficiently large input multiplexer is used then the data sampled at any one input will be random and a true mean and variance can be calculated. This technique is adequate for inputs that normally display a small variance, e.g., DC signals. Figure 8 is a more complex technique but yields better results on signals, such as vibration. This technique is known as Stochastic Ergodic Measurement (SEM). It is called stochastic because the conversion from analog to digital is statistical and probabilistic, and ergodic because ergodicity of the input signal is assumed. Practically all physically realisable signals can be considered ergodic.(14,13)

A fundamental difference between an SEM convertor and a standard ADC is that the reference signal of the SEM convertor is not constant but is randomly varying and can be defined only by its statistical behaviour.

When the input signal is compared with the random reference at periodic time intervals, a pulse is generated at the output and the input signal is greater. Therefore, the probability of a pulse occurring at the output is proportional to input voltage.

The final step in the SEM process is extraction of a measurement value from the output pulses. This can be done by counting the number of pulses that occur in a set measurement period. This digital count represents the input value.

Noise present in the input can be ignored by the SEM convertor because it is in itself random.

4.2 Input Data Screening

4.2.1 Estimation of Variance

The input data has already been partially cleaned up by the particular techniques employed in the ADC. Any noise present at the input will have been averaged out, except for any DC content which will be added directly to the input signal. It would therefore be desirable to know the noise content of the input data, allowing rejection of noisy data on the assumption it contains a DC error. The degree of variation or variance of the input data will provide a direct indication of noise content; rather than tediously calculating the variance; however, it should be sufficient to determine how many of the samples lie with specified limits of the average,

$$\text{i.e., } P(a<(x-\bar{x})<b) = \frac{N^{o} \text{ of samples } a<(x-\bar{x})<b}{\text{Total } N^{o} \text{ of samples}}$$

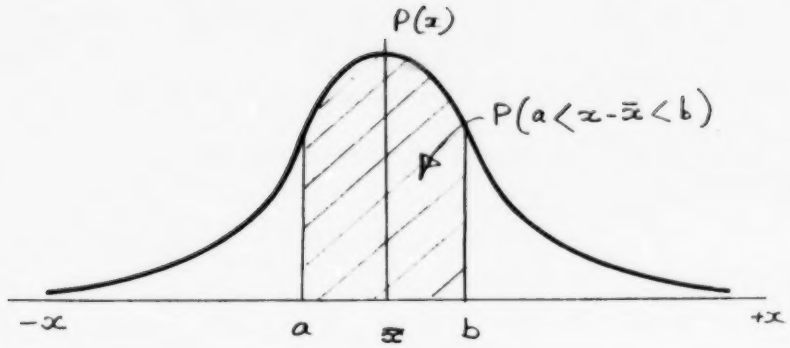

Figure 9 Probability Density Function

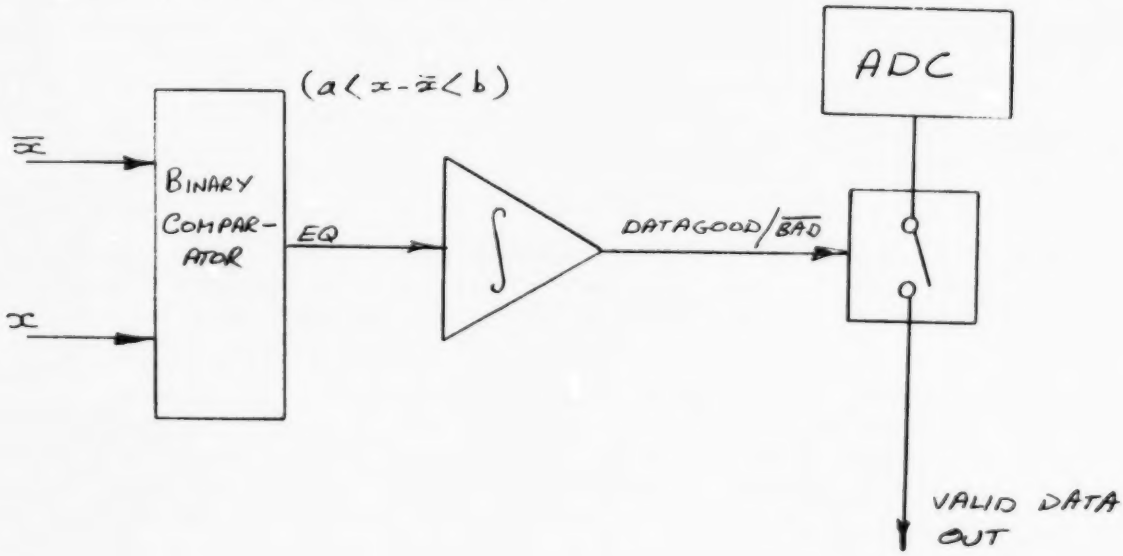

Figure 10 Data Screening Technique

Implementation of this technique in a computer is far more efficient than calculating the variance because fewer calculations have to be made. For example to calculate the variance over 16 samples requires:

48 additions 16 multiplications & 1 division.

To calculate the probability between limits over 16 samples requires:

32 additions & 1 division.

Note that each multiplication/division takes an average of 6 additions to complete, therefore

Calculation of variance requires 150 additions.

& Calculation of probability requires 38 additions.

This will impose a considerable workload on the system if many inputs have to be processed many times a second.

Hardware implementation of the probability calculations is straightforward and could be incorporated into the ADC sub-systems, eliminating all computation requirements. Figure 10 is a possible arrangement.

4.2.2 Calculation of $\overline{x}$

Exponential averaging and nomalized summation are the two techniques that can be used to average the input data samples.(15)

Nomalized summation is a straightforward averaging process where m samples are summed and the total divided by m. This technique is perfectly by adequate for analysis of a set of samples of pre-defined size taken from a stationary process.

In real time monitoring situations the exponential averaging technique 0 has the distinct advantage that it is a continuous updating process which forgets old information and thus follows changing phenomena. If $A_{(m-1)}$ is the current value of the running average and a new input I_m arrives then the new average is: -

$$A_m = A_{m-1} + (I_m - A_{m-1}) / m$$

This running average algorithm acts like an RC averaging circuit with a time constant approximately equal to m times Δt, the time between samples.

A powerful feature of the exponential averaging algorithm is the effect of the increasing value of m during the initial phase of measurement. Initially, m is one; then, as the measurement proceeds, the value of m is incremented. This has the effect of averaging with a capacitor whose value increases during the measurement. High-frequency noise is averaged out immediately, leaving the lower frequencies for later, thus giving a rapid preliminary estimate of the final average. After the first M samples have been taken, the weighting factor of the new sample remains M and hence no further change of time constant takes place.

The average is now

$$A_m = \frac{1}{M} \sum_{i=1}^{m} \left(\frac{M - 1}{M} \right)^{m-i} I_i$$

where i is the running index of input I. The weight of the (m-M)th sample is e^{-1}, which shows that the weighting factor of the samples taken reduces exponentially with a 'time constant' of M samples.

Digital exponential averaging has two important advantages - stability and flexibility - over the analog RC averaging method. It is more stable because it is not subject to the drift normally associated with analog circuits, and more flexible because changing the time constant entails not a change of physical components, but simply a changed divisor in the averaging algorithm. Digital averaging has the added advantage that it makes possible very long-time constants, and hence low-frequency analysis without physically large components. Time constants from a few milliseconds to many days represent no problem for digital integrators, but are quite impossible with RC averagers.

4.3 Data Reduction

The screened data is processed mathematically using thermodynamic, aerodynamic and mechanical models as appropriate. These models for the engine and the engine's major accessories, are used as basic tools for the reduction of the data into performance coefficients and component efficiencies. Part 3 describes this process in more detail.

4.4 Fault Vector Analysis

Every operating condition of the engine, whether a normal or an abnormal fault condition, can be represented by a vector. The elements of the vector are the selected measured parameters that define an operating condition.

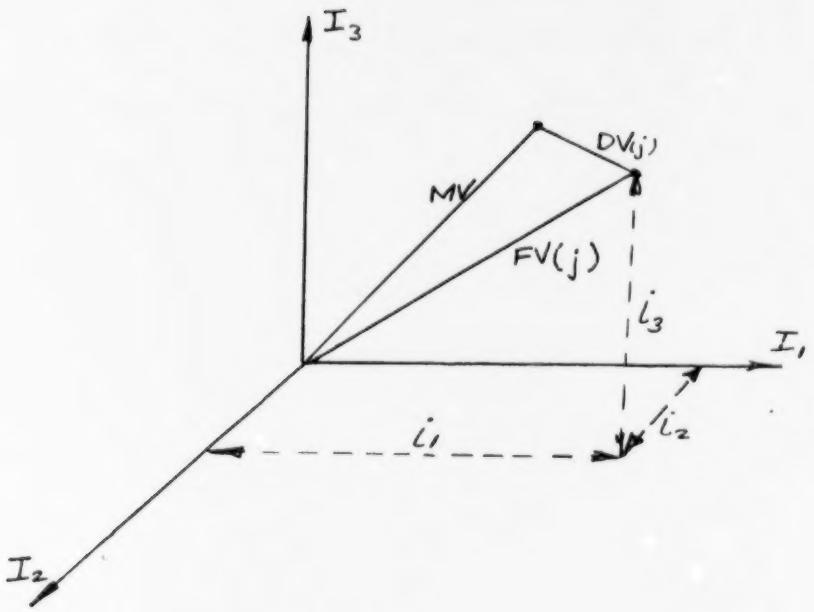

Figure 11 Fault Vector Analysis

A normal vector and a set of fault vectors is predefined for the engine. These vectors must be defined for a number of different operating (power or speed) levels of the engine and classified by length or distance from the origin. This can be determined by calculating the root of the sum of squares:

$$L_v = \sqrt{\sum_{i=1}^{n} (FV_{(i)})^2}$$

where L_v = vector length

FV = Fault Vector

i = Fault Vector element index.

4.4.1 Diagnosis

Diagnosis of a fault condition is achieved by comparing a measured vector with any number of fault vectors of similar length. The most probable fault is the fault vector with the shortest geometric distance from the measured vector.

The geometric distance on difference vector (DV) is calculated by the sum of least squares:

$$DV_j = \sum_{i=1}^{n} (FV_{j,i} - MV_{(i)})^2 \qquad \begin{array}{l} \text{for } j = 1 \ldots -m \\ \text{and } i = 1 \ldots -n \end{array}$$

where j = vector index

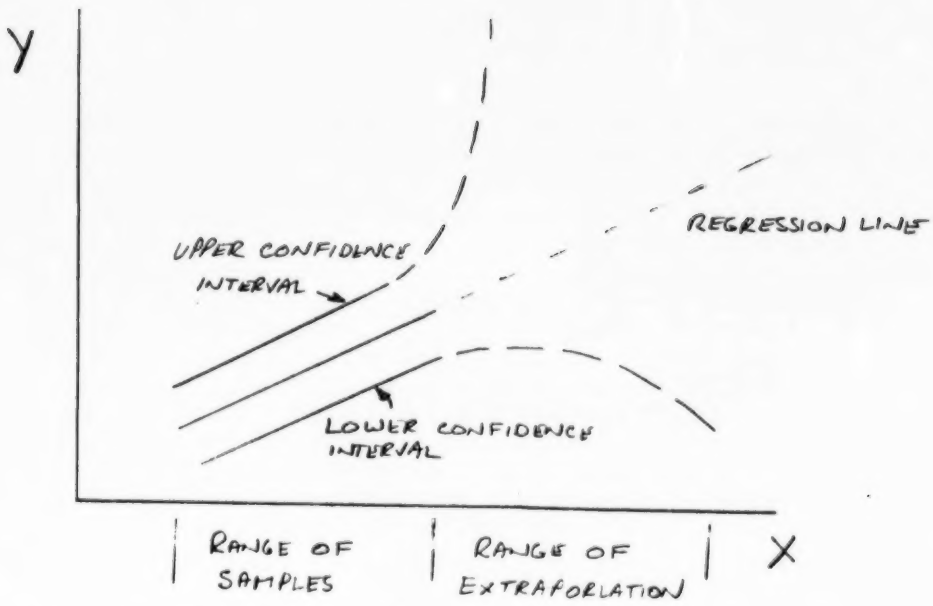

Figure 12 Confidence Intervals for Linear Regression

The probability of fault decreases with increasing geometric distance; therefore, the most probable fault can be determined, as can several less probable but possible fault conditions.

There always exists the possibility that a fault occurs for which a vector has not been previously identified. This condition would not go unnoticed, it would be seen as an increasing difference vector from the normal vector even though a diagnosis could not be made with any degree of confidence.

4.5 Trend Analysis

A trend in a measured variable (or in this case a vector) can be a useful indicator of an approaching fault condition. The technique used is linear regression analysis. However, these techniques must be used with caution.

Statistics is a science of classifying and manipulating data in order to draw inferences, i.e., samples are drawn from a large population to estimate the true mean of the population. Since statistics provide only an estimate of the true value of a parameter, then the estimate can only be made with a certain degree of confidence. For example, one could state: "we are 95% confident that the true value of the exhaust gas temperature lies between 385° and 395°C. In other words the 95% confidence interval limits are +5°C from the estimated value. See Figure 12.

Regression techniques are generally used to predict values of Y for a given X within the range of the chosen values of X used to obtain the regression line. Values of Y outside of this range can be predicted, however, by extrapolation beyond the observed range of the independent variable X, but it is extremely hazardous. Two problems arise: first, the regression line may be a higher order function outside of the observed values; and second, the width of the confidence interval increases proportional to $(X^1 - \bar{X})^2$ where X^1 is the value used to predict Y and X is the mean of the observed values. This means that because of the very much wider confidence interval of the predicted value an apparent trend is in fact no trend at all. This serves to illustrate that a very high correlation is required between variables to ensure that the confidence interval does not become too wide when a prediction is made, and that the regression line is in fact straight. Proper screening of the input data as described should reduce the confidence interval sufficiently to enable a reasonable prediction to be made.

4.6 The Computer System

4.6.1 Background

The computer system used will be one currently under development by GEM Data Systems Inc., an associate company of Eyretechnics.

GEM has undertaken the development of a new mid-sized computer system using next generation design principles. Development of such a computer is essential to the successful completion of the GAMMA project.

The development of this computer was undertaken for the following reasons:

- a relative lack, at affordable prices, of computers with adequate performance for fast process control and/or analytic or diagnostic monitoring of mechanical or biological systems.

- a realization of the performance limitations, interfacing complications, and expansion incompatibilities of most current systems.

- a desire for self-sufficiency and assured supply of a relatively unchanging product.

- and, last but not least, some four years of research and experiments toward the design of a practical computer with minimum obsolescence and maximum size and flexibility.

Our experience and research have indicated that a multiple processor, shared memory computer would best suit our needs and objectives.

By virtue of its multi-processor, firmware driven design, the computer system has the following inherent properties:

- accordian-like performance expansion capabilities by addition of more processing (or correlating) modules.
- automatic software compatability for full range of configurations.
- very near total redundancy at most operation levels.
- built-in capacity to absorb several generations of higher performance components.

Therefore, this design scheme would have a particularly high performance/price advantage when used for multi-loop process control, large data acquisition, multi-user data retrieval, and fully diagnostic health monitoring.

The novelty of the computer system resides in good part in unique construction details, but two novel system features should be stressed. In existing commercial computers that use many processes initially, each processor is specialized in function, with a designated processor having master control of the system. In this scheme, no processor is dedicated (through some are optimized) and system control is in memory (firmware) not in a processing or computing element.

4.6.2 Technical Brief

Following are some of the basic design principles being used in the development of the computer system.

- Memory throughput rates in large part determine system performance, but are considerably higher than can be absorbed by single processors; therefore, several processing sub-systems, henceforth called correlators, can and should be served simultaneously by an "intelligent" memory interface to ensure full use of every memory cycle.
- To simplify system control, and to make correlators equal and redundant, system control shall reside in central memory through a firmware "conscious" centre called EGO (Executive Group Operator).
- To make EGO independent of processor machine language, it shall consist of data structures (tables, directories) and system state algorithms in a simple interpretable language.

- All correlators (sub-systems) shall have the ability to interpret EGO, as provided by firmware in their local memories.

- The processor module of the different correlators, whether data processors, I/O controllers, or system control consoles, will be a multi-port building block with universal external interfacing, to simplify implementation of the various types of correlators.

- The physical packaging will be ruggedized, and of the same design whether for industrial or military specification, with only component grade changes between the two versions.

5. COST/BENEFIT ANALYSIS

5.1 System Life Cycle Costs

The life cycle costs of the diagnostic health monitoring system have been estimated assuming the system will have a useful life of 15 years. Development costs have been distributed over a production run of 15 systems (the number of CN Marine vessels that could benefit from a system). The costs of one shipset of equipment are based on the MV Holiday Island/Vacationland installation.

5.1.1 Development Costs - Phase II and III

Equipment

Computer System	$25,000	
Transducer Interface	10,000	
Transducers	28,000	
Development Tools	30,000	
Total		$93,000

Labour Manhours	Eng.	Tech.
System Design	10	4
In-House Development	8	
Field Development	8	5
Data Collection	3	4
Environmental Testing	1	1
Application Testing	6	4
Total	36	18

Engineer/Analyst 36 man months @ 8000.00/month	$288,000
Technologist/Draftsman 18 man months @ 5000/month	$ 90,000
Travel	$ 25,000
Total Labour	$403,000
Total Development Costs	$496,000

5.1.2 Equipment

Estimated costs for the installation of a complete health diagnostic system for two engines and ancilliaries on the MV Holiday Island or MV Vacationland are:

Computer System	$23,000	
Transducer Interface	20,000	
Transducers	40,000	
Installation	2,000	
Total		$87,000

5.1.3 Operating Costs

Estimated operating costs for the equipment described in 5.1.2 are:

Training per Year	$2,000	
Maintenance per Year	5,000	
Total		$7,000

Administrative, manpower and electrical costs are considered negligible.

5.2 Benefits

The largest benefit to be realized from the fitting of engine health diagnostic system is expected to be in improved engine efficiency and reduced fuel consumption.

Conceivably, due to the increased surveillance that such a system would offer, engine room manning could be reduced, reducing operating costs. At the present time and in the foreseeable future manpower reductions are probably not possible due to classification society and government regulation.

Changeover to a maintenance system based on condition instead of the strictly scheduled systems now in use is again limited by classification society and government rulings.

In the particular case under study the MV Holiday Island/ Vacationland yearly fuel consumption is estimated to be 3,000 lbs. With the cost of fuel currently at $.20/lb. the annual cost would be $600,000. The total fuel consumption estimate is based on a fuel consumption for 1.125 tonnes/hr and the published sailing schedule.(16)

5.2 COST/BENEFIT SUMMARY

Annual fuel cost per ship, using $.20/lb:		$600,000
Assuming fuel cost increases at 5% p.a. above inflation, then total fuel cost over estimated useful life of diagnostic system (15 years):	600,000	
compounding factor:	x 21.5786	$12,947,160
Estimated fuel saving is 5% total fuel cost saving over 15 years =		$647,358
Estimated development cost per ship:		$33,067
Estimated cost of equipment per ship set:		$87,000
Financing cost estimated at 5% return over inflation:	33,067	
	+ 87,000	
	120,067	
compounding factor:	x 2.0789	$249,607
Operating costs per annum estimated at:		$7,000
Assuming operating costs increase at inflation rate, then total operating costs are:	$7,000	
	x 15	$105,000
total installation and running costs per ship over 15 years are:	249,607	
	+ 105,000	$354,607
and total savings per ship, using diagnostic equipment are:	647,358	
	- 354,607	$292,751

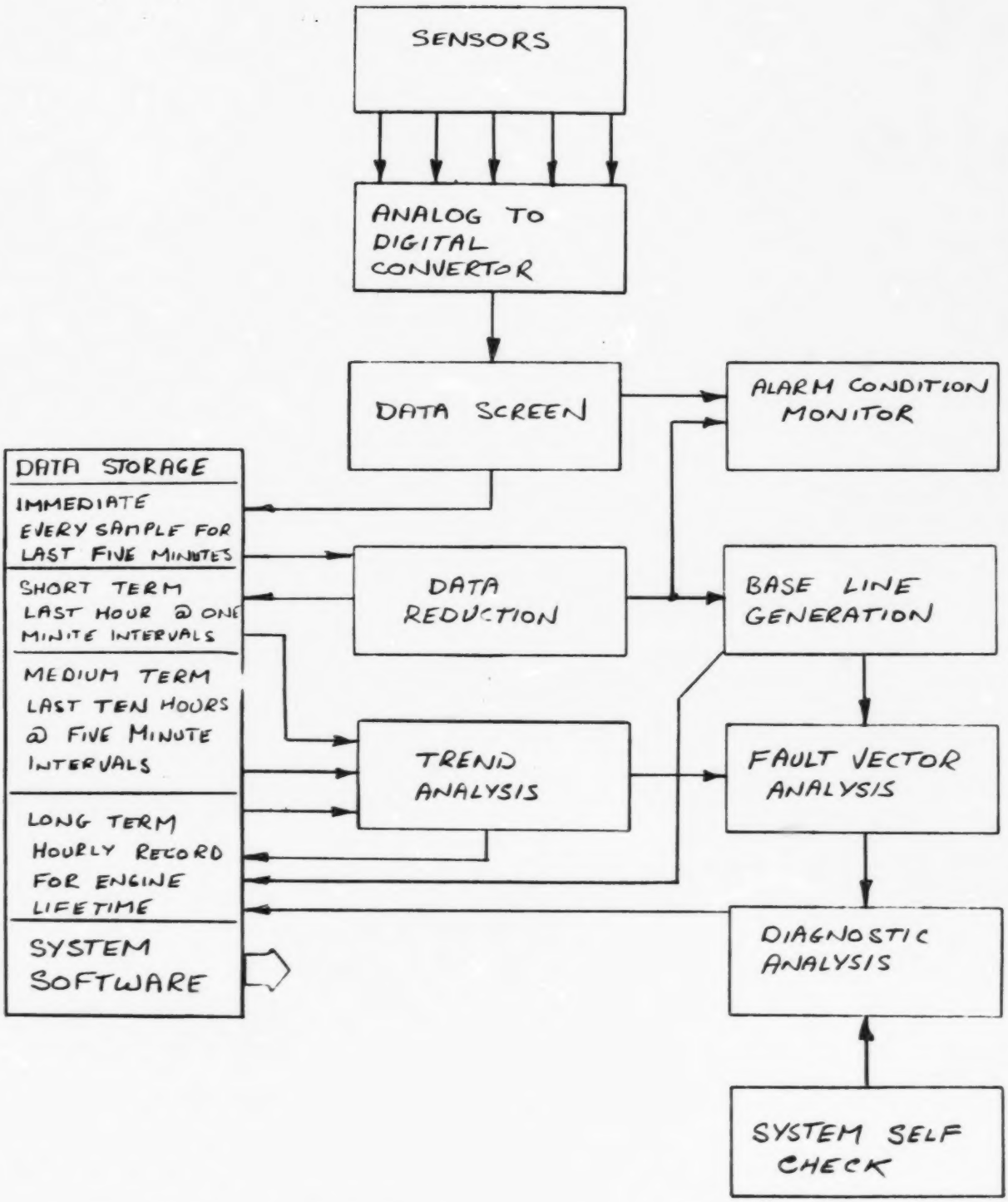

Figure 13 System Organization

6. FURTHER DEVELOPMENT

Phase I has been completed and the feasibility demonstrated. In addition, the basic structure of the propulsion system of the health diagnostic system has been laid down.

Phase II will consist of the collection and analysis of a substantial quantity of data from a running engine. During this phase the cooperation of the engine manufacturer should be enlisted to enable some of the data to be collected from the more clinical test cell environment. The basic computer system would be supplied during this phase and used primarily to collect the data required. By the end of this phase the algorithm for analysis and preliminary diagnostics will have been established.

During Phase III the analysis algorithm and the preliminary diagnostics will be installed in the computer system. Further operating experience during this phase will enable the development of reliable diagnostics.

Phase IV will be an observation and fine tuning phase. The main purpose of this phase is to prove the reliability of the system from both hardware and diagnosis points of view. Once reliability is proved it is hoped that change in the classification society rulings can be initiated, therefore allowing for greater savings in reduced manpower and scheduled maintenance costs.

REFERENCES

1. Relation Between Form of Cylinder-Pressure Diagram and Noise in Diesel Engines, by T. Priede, I.Mech.E, 1/60-61.

2. Simple Model Technique for Better Understanding of Diesel Engine Vibration and Noise, by K. Ochiai, M. Aisaka and S. Sakata, SAE, August 75.

3. Condition Monitoring of Diesel Engines, by M. Langballe, L. Tonning and T. Wibors, Norwegian Maritime Research, 3/75.

4. In Search of Origins of Engine Noise - An Historical Review, by T. Priede, SAE, Feb. 80, Detroit.

5. Effect of Piston Slap on the Noise and Vibration of Diesel Engines, by H.L. Pullen and S.D. Haddad, Brit. Acoustical Soc, July 73.

6. Study of Lateral Vibration of Large Diesel Engine. Mitsubishi, 1970.

7. Relation Between Crankshaft Torsional Vibration and Engine Noise, by K. Ochiai and M. Nakana, SAE, 1979/80.

8. Application of Vibration Signature Analysis and Acoustic Emission Source Location to On-Line Condition Monitoring of Anti-Friction Bearings, by L.M. Rogers, Tribology International, April 1979.

9. Detection of Rolling Element Bearing Damage by Statistical Vibration Analysis, by D. Dyer and R.M. Stewart, ASME, 77-DET-83.

10. Techniques of Vibration Analysis Applied to Gas Turbines, by R. Chisholm Gas Turbine International, Nov/Dec. 1976.

11. A Short Course on Digital Analysis, by J. Pollock and Bob Kaiser, ASME, New Orleans, La., March 1980.

12. Automation of High-Powered Diesel Machinery, by R. Munton and J. McNaught, I.Mar.E, June 66, Munich.

13. Shift Register with Feedback Generators White Noise, by Marc Damashek, Electronics, May 27, 1976.

REFERENCES (cont'd)

14. New Instruments use Probabilistic Principles, by Tumfart, Siegfried, Electronics, July 24, 1975.

15. Analog Signal Processing and Instrumentation, by Arbel A.F. Cambridge University Press, 1980.

16. Handbook of Vessels and Terminals, CN Marine, Oct. 1980.